EXTREMELY INSENSITIVE DETONATING SUBSTANCE TESTS

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ABSTRACT

The United Nations (UN) Committee of Experts on Transportation of Dangerous Goods approved a new test protocol (UN Test Series 7) and a new hazard class/division (C/D 1.6) in 1988. C/D 1.6 was developed to classify extremely insensitive explosive articles that contain only extremely insensitive detonating substances (EIDS) as determined by passing the criteria of UN Test Series 7. The United States Air Force has played a major role in advancing the development of EIDS. This paper describes in particular, the current substance tests of Test Series 7, some of their shortcomings, and recommendations for improvements in these tests. Formulation effects for bomb and warhead fills are described elsewhere. [1,2].

INTRODUCTION

Over the past twenty years, there has been demonstrated a need for less-sensitive explosive fills for munitions that maintain or exceed current explosive performance. The benefits to be gained include greater materiel and personnel safety in all logistics phases in the munitions' life-cycle, and the potential for increased munitions density in land-limited storage areas that are adversely affected by encroachment of civilian populations. In the United States, the military services and the national laboratories have provided the driving forces for the development of less-sensitive explosives, through the promulgation of needs documents, numerous advisory committees, and the ultimate publication of military standards on how to determine whether a substance or an article is indeed insensitive [3,4,5,6]. In Europe, the North Atlantic Treaty Organization (NATO) has been the focal point for a similar effort, culminating in guidelines to be used for the testing, storage, and transportation of extremely insensitive explosive articles (now called "EIDS Ammunition") [7]. The history of the development of these tests and standards has been summarized by Ward [3] and Swisdak [4]. Currently, the United States is undergoing major revisions to DOD 6055.9-STD [5,8] to implement the UN hazard classification tests and criteria for C/D 1.6 [8].

UN TEST SERIES 7

UN Test Series 7 requires passing all of the tests at the substance level before testing is performed on articles, generally in their transportation configuration. These tests are summarized briefly in Table I. Part A describes the tests to be performed on substances. Passing all of the substance tests allows the material to be categorized as an Extremely Insensitive Detonating Substance (EIDS), and permits article tests to be performed. Part B of Table I describes the tests to be performed on actual articles filled with EIDS. If the articles pass all of these tests, they can be assigned UN hazard class/division 1.6, allowing increased storage density over that for other hazard categories.

EIDS TESTS, PROBLEMS AND SOLUTIONS

In the United States, six types of EIDS test are performed at the substance level. These include a #8 blasting cap test, an extended card gap test (at one fixed gap), external fire, slow cookoff, bullet, and SUSAN impact tests. In Europe, the friability test may be substituted for the bullet impact and the SUSAN impact tests. Testing apparatus and methods are documented in UN Test Series 7 [7].

EIDS Cap Test - The EIDS cap test is straightforward, testing for the detonability of the explosive material in response to initiation of a #8 blasting cap. It is performed in triplicate. Figure 1 shows a typical passing test result.

EIDS Gap Test - The EIDS gap test is a variant of the Expanded Large-scale Gap Test (ELSGT) developed at the Naval Surface Warfare Center, White Oak. [10]. The test is performed in triplicate. The hardware is well-specified in the UN Test Series 7 documentation, providing wall thicknesses and specifications for materials of contruction for both the explosive-filled tube and the witness plate. The difference between the Navy test and the UN test, is that the UN test is only run at one fixed gap (70 mm). This gap will attenuate the donor shock to about 53 kbar at the end of the gap. Unfortunately, it provides no information on the real shock sensitivity of the explosive fill. For example, in the sympathetic detonation of MK-82 bombs, the diagonal acceptor experiences in excess of 70 kbar, and may detonate even though it is classified as an EIDS. Also, while the scale of the test is more realistic than the NOL Large Scale Gap Test (1/2 the scale of the ELSGT), the test item may still be too small for many of today's insensitive high explosives having a large critical diameter. There is no provision for measuring explosive critical diameter in UN Test series 7. Three examples of passing reactions are shown in Figure 2.

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TABLE 1. UN TEST SERIES 7
FOR CLASS/DIVISION 1.6 ARTICLES
A. EXTREMELY INSENSITIVE DETONATING SUBSTANCE TESTS

TEST NUMBER	TEST NAME	NUMBER OF TRIALS	TEST VEHICLE	FAILURE CRITERIA
7(a)	EIDS Cap Test	3	No. 8 blasting cap in explosive contained in 80 mm x 160 mm cardboard tube and resting on a 1 mm thick steel plate.	Detonation as evidenced by hole punched in witness plate.
7(b)	EIDS Gap Test	3	73 mm x 280 mm Steel Pipe with 70 mm long Plexiglas gap between Pentolite donors and explosive fill, and resting on a 20 mm-thick witness plate	Detonation as evidenced by hole punched in witness plate.
7(c)(i)	SUSAN Test	5	51 mm x 102 mm explosive billet in aluminum cup as nose of massive steel projectile. Launched from 81.3 mm gun @ 333 m/s into steel wall.	$\geq$27 kPa overpressure at 3.05 m.
7(c)(ii)	Friability Test (Alternate for SUSAN test)	3	Explosive billet 18 mm diameter launched at 150 m/s into standard wall. Impacted material burned in closed bomb.	>15 MPa/ms pressure rise rate in closed bomb.
7(d)(i)	EIDS Bullet Impact Test	6	Single 50-caliber AP bullet impact into explosive-filled 45 mm id x 200 mm steel pipes with torqued end caps.	Explosion or detonation.
7(d)(ii)	Friability Test (Alternate for EIDS Bullet Impact Test)	3	Explosive billet 18 mm diameter launched at 150 m/s into standard wall. Impacted material burned in closed bomb.	>15 MPa/ms pressure rise rate in closed bomb.
7(e)	EIDS External Fire Test	3	Explosive-filled 45 mm id x 200 mm steel pipes with torqued end caps tested in kerosene-soaked wood fire. Five items per trial or fifteen in one trial.	Detonation or >15m fragment throw.
7(f)	EIDS Slow Cookoff Test	3	Explosive-filled 45 mm id x 200 mm steel pipes with torqued end caps tested to destruction at 3.3°C/hr rise in temperature.	Detonation or >3 fragments.

B. ARTICLE TESTS

TEST NUMBER	TEST NAME	NUMBER OF TRIALS	TEST VEHICLE	FAILURE CRITERIA
7(g)	1.6 Article External Fire Test	1	Ammunition in shipping configuration containing EIDS in kerosene-soaked wood fire. Three items, minimum.	C/D 1.1, 1.2, or 1.3 response
7(h)	1.6 Article Slow Cookoff Test	2	Ammunition containing EIDS heated to destruction at 3.3°C/hr rise in temperature.	> Burning
7(j)	1.6 Article Bullet Impact Test	3	Ammunition containing EIDS subjected to triple 50-caliber AP bullet impact.	Detonation
7(k)	1.6 Article Stack Test	3	Ammunition containing EIDS in both unconfined and confined shipping configuration stacks.	Propagation

EIDS SUSAN Test - This test gives a measure of the formulation's sensitivity to crushing impact. Standard procedures have been developed by Lawrence Livermore National Laboratory for this test. Presently there is only one facility that is capable of performing the test in the United States (New Mexico Institute of Mining and Technology, TERA facility, Socorro, New Mexico). While the procedure allows casting 51 mm x 102 mm explosive billets and then placing them in the "SUSAN cup" (the nose of the projectile), most explosives are simply cast in place. If the explosive is placed in the cup after cure, care should be taken to bond the explosive to the cup. Otherwise, variable test results can be obtained. Five tests are performed. Figure 3 shows the SUSAN projectile and its aluminum SUSAN "cup" nose filled with explosive.

EIDS Bullet Impact Test - Six steel pipes are filled with explosive, sealed with torqued end caps, and tested in triplicate in each of two orientations. (See discussion of pipes, following). Each pipe is impacted by a single 0.50-caliber armor-piercing bullet. Three are impacted on the side of the pipe, and three are impacted through the endcap along the long axis of the container. Reaction violence is recorded. Typical passing reactions are shown in Figure 4.

EIDS External Fire Test - 15 steel pipes (see discussion of pipes, below) are loaded with explosive and sealed with torqued end caps. Triplicate tests of 5 pipes each may be performed or one test with all 15 pipes can be performed. These are subjected to a fuel-soaked wood bonfire of specified geometry and materials. Figure 5 shows a typical set up in progress. Witness panels of thin aluminum are placed 4 m away on three sides of the fire to help gauge reaction. The test layout, while well-described in the UN document, leaves much to the experience of the test engineer. Attachment of the pipes to a grate and the design of the grate are unspecified. At best, this kind of fire is variable, and ambient weather conditions influence the test significantly. The use of kiln-dried wood stacked 100 mm apart, and at right angles every other layer, provides the best fire. There are a number of problems and suggestions for improving this test. First, good video coverage is required over a wide field of view to help spot the location of pipes after reaction. The video coverage should also provide audio coverage, so that the number of reacted pipes can be counted as they react. Many times, a number of the pipes exposed to the fire do not react, but lofted out of the fire by ones that do react. These pipes may contain partially reacted explosive. Therefore, a standard waiting period of at least eight hours after the test is completed should be required. After mapping the debris, the unreacted units need to be disposed of. This disposal can be quite hazardous if done improperly. A disposal procedure should be in place before attempting to perform this test. Figure 6 shows typical passing test results and a number of unexploded pipes requiring disposal.

EIDS Slow Cookoff Test - Three steel pipes (see below) loaded with the explosive of interest are individually subjected to a slow, specified temperature rise in an oven. Each is tested to destruction, while the air and item temperatures are monitored with thermocouples. We have found that commercially available "toaster ovens" with a top and bottom heating element can be economically modified to perform this test. Thermostats are removed, and the heating elements are directly connected to the proportional controller. A 3-inch-diameter pancake fan (available from Radio Shack) is inserted on the same wire rack as the test item to circulate the air. We have found that the orientation of this fan is critical to getting reproducible test results. It should be placed horizontally on the rack to circulate the air from bottom to top of the oven. If it is placed vertically to circulate air side to side, large temperature gradients are observed. A typical test set up is shown in Figure 7. There are a number of items to remember when performing this test. First, the test takes a long time -- typically 12 - 30 hours. This can impede the performance of other tests at the facility. Second, it needs to be performed in an area large enough to accomodate the launching of the heavy pipe endcaps without hazard to other operations. Finally, continuous video coverage is desireable to record reaction violence, but since the end time of the test is indeterminant, provision must be made to change videotapes remotely every eight hours. Third, since the test is of long duration, night lighting for the video coverage is imperative. ARC uses an expendible halogen outdoor light. Figure 8 shows a typical passing reaction in which the bomb body has not fragmented at all.

Pipes - Of all the test geometries and containers, perhaps the one type with the biggest potential for variability in results is the "pipe bombs". The same 45-mm-id x 200-mm long (in the US, 1-1/2 x 8-inch schedule 40 seamless steel pipe) container with 4-mm wall thickness is used for bullet impact (6), slow cookoff (3) and fast cookoff (15) tests. These pipes are first loaded with the explosive of interest. In the case of cure cast systems, one end of the clean, grit-blasted pipe is blanked off, while it is filled from the other end in a vacuum casting bell. Regardless of how good your casting technique is, some explosive always gets into the pipe threads, and must be removed prior to installing the end caps. The open end is then covered and the filled pipes are placed in the cure oven.

After curing, the protective coverings are removed, and the threads scrupulously cleaned. This is a tedious and time-consuming job. Once the threads are certified as free of explosive, the endcaps are ready to be installed. This requires a special remote operation fixture, in which the loaded pipe body is held in a sturdy vise, and the first endcap is placed in the tightening fixture. This consists of a long steel rod with set screws to hold the pipe cap (at one end), and proceeding through the steel protective barrier to a fitting that mates with a large torque wrench on the other end. The pipe cap is threaded onto the pipe until resistance is encountered, then the requisite 204 N-m (150 ft-lb) torque is applied to that endcap. Note that this is a significant torque setting, requiring a skilled, strong person to get reproducible results. Once the first endcap is installed, the pipe is unfixtured, turned 180 degrees, and the whole remote procedure repeated for the other end. With practice, the average turnaround time per bomb is somewhat under 10 minutes. Thus, for one EIDS test series of 24 pipes, 240 minutes (4 hours) will be used just to tighten end caps, and an equal or greater time will be used just to clean and certify the threads as free of explosive.

There are problems that can be encountered, both with the pipes and with the end caps. The pipe is supposed to be seamless steel pipe, but no specification is given in the UN document. There are at least two ASTM specification numbers and at least 5 grades of seamless carbon steel pipes [10]. The chemical compositions of these carbon steels are identical, but those meeting ASTM Specification A106 have been tested more thoroughly. Both ASTM A53 and A106 are made in Grades A and B. A106 is also made in Grade C. Tensile strength increases with Grade letter, while ductility decreases. Tensile strength at room temperature is 48,000 psi for Grade A; 60,000 psi for Grade B; and 70,000 psi for Grade C. There also exist various welded pipes including butt welded, lap welded and electric fusion welded. While these have tensile strengths on the order of Grade A seamless pipe (ca. 40-45,000 psi), their useful service temperature is significantly lowered. We have on occasion received pipe certified as seamless that was obviously welded along a straight seam and, upon reaction, failed along the seam line. This

is shown graphically in Figure 9. Pipe end caps are only specified as steel or cast iron. We have found that the material of construction, its finish, and its form of fabrication can influence the test results. We have tested with end caps of cast iron and of steel, as well as galvanized steel. Ungalvanized steel is the best choice. Galvanized steel can catalyze early reactions with the explosive in the cookoff scenarios and is to be avoided. Pipe caps meeting general plumbing standards vary significantly. We have used steel endcaps from a number of US manufacturers, as well as ones from Mexico and from Thailand. Those of foreign manufacture were significantly worse in the EIDS tests than those from domestic sources. Within the end caps produced in the United States, there was significant variation in the cap geometry. Apparently, pipe cap geometry is something of an art form in the plumbing world. Caps range from unlabeled to inscribed to those with raised lettering. This lettering may be anywhere on the cap. Lettering may act as a stress riser. There are those with flat ends of uniform wall thickness and those that are dome-shaped with variable wall thickness. Those that are flat tend reproducibly to punch out a disc of the pipe inner diameter, and at relatively low pressures, thereby venting the system early and minimizing any pipe sidewall reactions. Those that are domed generally stay attached to the bomb until pressure rupture occurs, almost always failing at the first exposed thread beyond the attached endcap. Note that these endcaps can become hazardous fragments because of their large mass and velocity.

EXTREMELY INSENSITIVE PLASTIC-BONDED EXPLOSIVES TEST RESULTS

In our explosives development work ARC has formulated a number of insensitive explosives that have been subjected to the EIDS small-scale test series, and several that have been carried on to the article level. These formulations have all incorporated fine nitramines to reduce shock sensitivity, aluminum and ammonium perchlorate as blast impulse enhancers, and varying amounts of nitroguanidine as a coolant and burning rate modifier. The test results to date are shown in Table 2.

TABLE 2. UN TEST SERIES 7 RESULTS FOR INSENSITIVE EXPLOSIVES DEVELOPED BY ATLANTIC RESEARCH CORPORATION

TEST TYPE	Formulation A RDX/Al/NQ	Formulation B RDX/Al/AP	Formulation C RDX/Al/AP/NQ	Formulation D RDX/Al/AP/NQ	Formulation E RDX/Al/AP/NQ
EIDS Cap	PASS	PASS	PASS	PASS	PASS
EIDS Gap	PASS	PASS	PASS	PASS	PASS
EIDS SUSAN	PASS	PASS	PASS	PASS	PASS
EIDS Bullet Impact	PASS	PASS	PASS	PASS	PASS
EIDS External Fire	PASS	PASS	PASS	PASS	PASS
EIDS Slow Cookoff	PASS	PASS	PASS	PASS	PASS
ARTICLE External Fire	NT	Propulsive burning in MK-82	Propulsive burning in MK-82	PASS - in MK-82	1 PASS/1 Mildly propulsive burning in MK-82
ARTICLE Slow Cookoff	NT	PASS - in MK-82	NT	NT	1 PASS/1 Pressure burst in MK-82
ARTICLE Bullet Impact	NT	PASS - in MK-82	NT	NT	1 PASS in MK-82
ARTICLE Stack	NT	PASS - ADJACENT in MK-82 Stack of 6 FAIL - DIAGONAL in MK-82 Stack of 6	PASS - ADJACENT in MK-82 Stack of 6 FAIL - DIAGONAL in MK-82 Stack of 6	PASS - ADJACENT in MK-82 Stack of 6 PASS - DIAGONAL in MK-82 Stack of 6	PASS - ADJACENT in MK-82 Stack of 6 PASS - DIAGONAL in MK-82 Stack of 6
EIDS Substance?	YES	YES	YES	YES	YES
EIDS Ammunition?	NT	NO	NO	NT	YES

[a] TBD = To be determined [b] NT = Not tested

While all of these explosives are extremely insensitive detonating substances, most have not passed all of the subsequent article tests. There seems to be little connection between the EIDS external fire test results and the article results. Also, there is a problem relating the EIDS gap test to sympathetic detonation response in the article stack tests. However, through careful formulation to maintain performance while decreasing sensitivity, formulation E is both an EIDS, and MK-82 bombs loaded with formulation E are EIDS ammunition.

RECOMMENDATIONS AND CONCLUSIONS

In this paper, some lessons learned have been presented that relate to the testing of insensitive high explosives. It must be remembered that UN Test Series 7 is used to classify articles for storage and transportation purposes, and that the tests are not meant to be used to obtain quantitative explosive and article sensitivity data. This is unfortunate since threshold sensitivity data could be obtained in some of the tests. For example, performing the EIDS gap test at different gaps after starting at the 70-mm gap would be useful for better predicting sympathetic detonation response. Additionally, a point of clarification needs to be added to the UN Test Series 7 EIDS pass/fail criteria. While it is implied, it is not at all clear that the side wall of the pipe bombs is all that should be taken into account. Endcaps should not be included in the evaluation, since the real criterion for these tests is distinguishing between detonation and no detonation by the fragmentation of the side wall.

To obtain more consistent data between test facilities, much tighter specifications are required for the 45-mm x 200-mm pipes and their endcaps. ARC recommends the use of ASTM A53 Grade A seamless steel pipe and A53 Grade A steel endcaps that have a radius of curvature on the end and either cast, raised lettering or no lettering on the end cap. These materials are widely available in the United States. For the external fire test, a suggested improvement that would minimize early fire conditions would be to insert the grate with the attached rounds into a fully developed fire (e.g., via a gantry arrangement) instead of starting the fire with the rounds already in place. This would provide a more uniform basis for comparison of tests performed at different facilities.

Atlantic Research Corporation has a developed a significant EIDS testing database while formulating insensitive explosives for the US Air Force. A number of EIDS formulations have been developed. Although these formulations are extremely insensitive to hazards stimuli, they have been shown to also have good performance characteristics.

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Figure 1. EIDS cap test.

Figure 2. EIDS gap test.

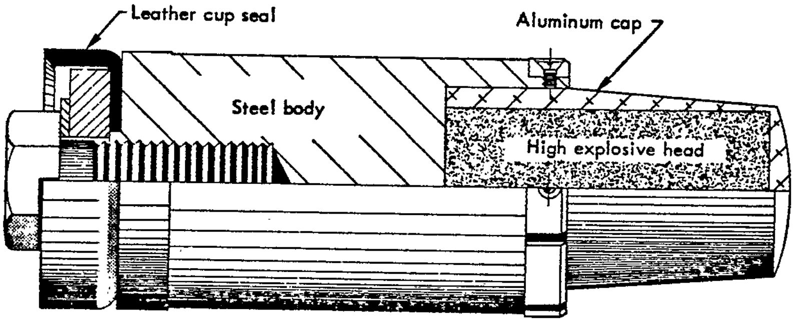

Figure 3. EIDS SUSAN test.

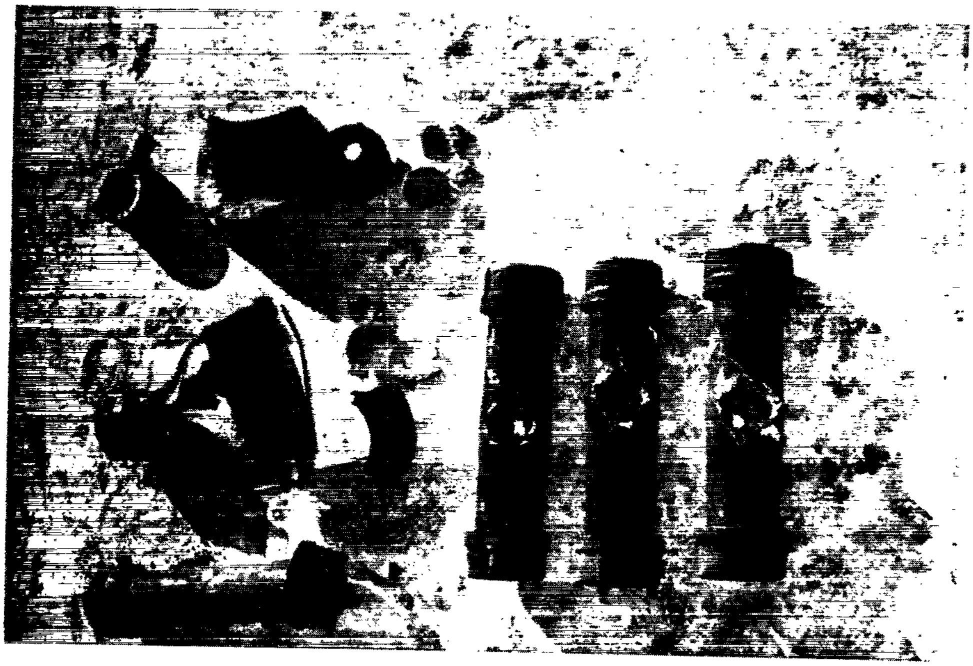

Figure 4. EIDS bullet impact test.

Figure 5. EIDS external fire test setup.

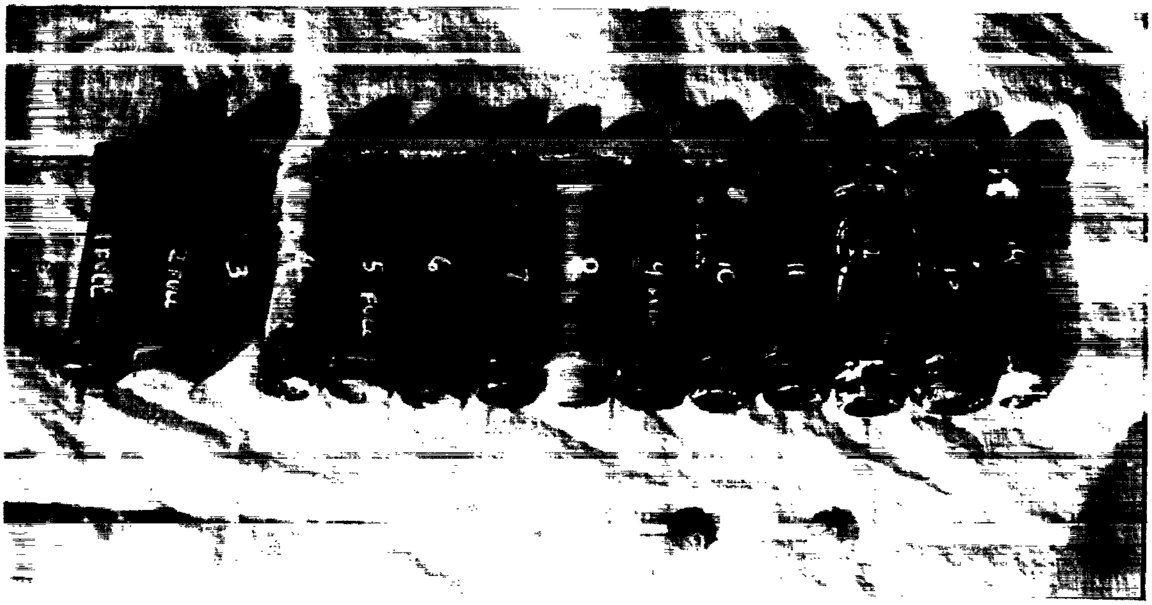

Figure 6. EIDS external fire results.

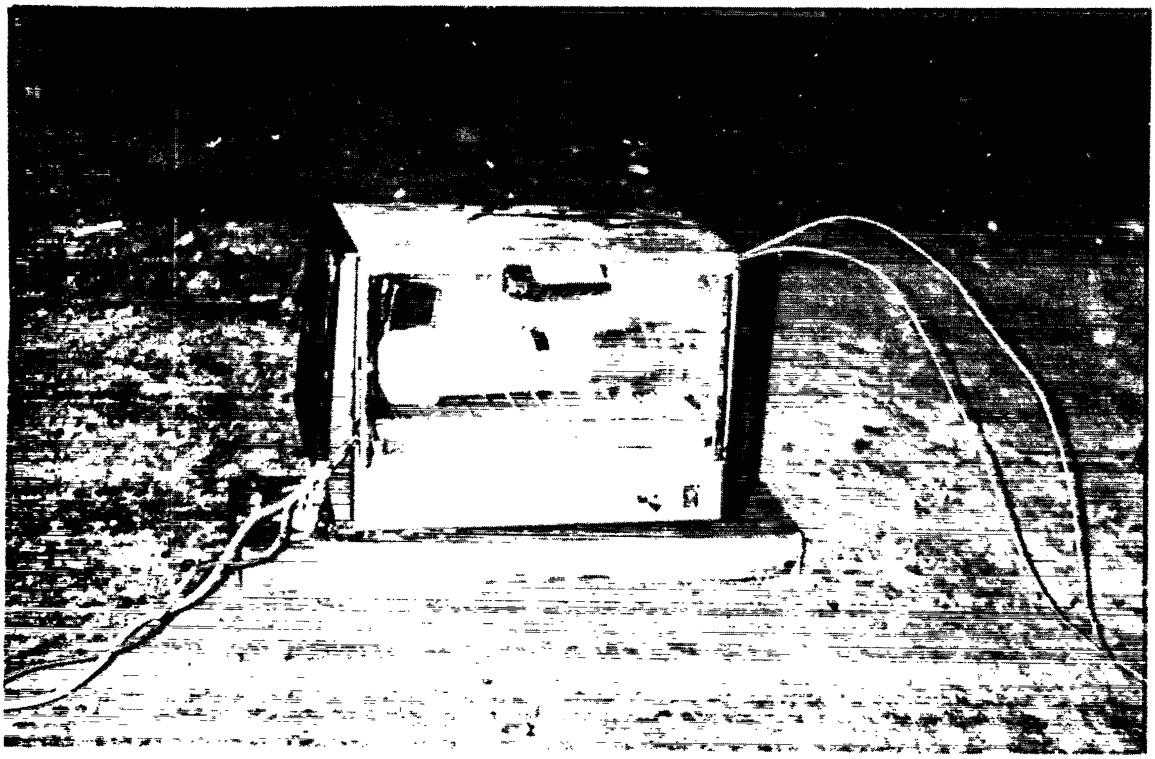

Figure 7. EIDS slow cookoff test setup.

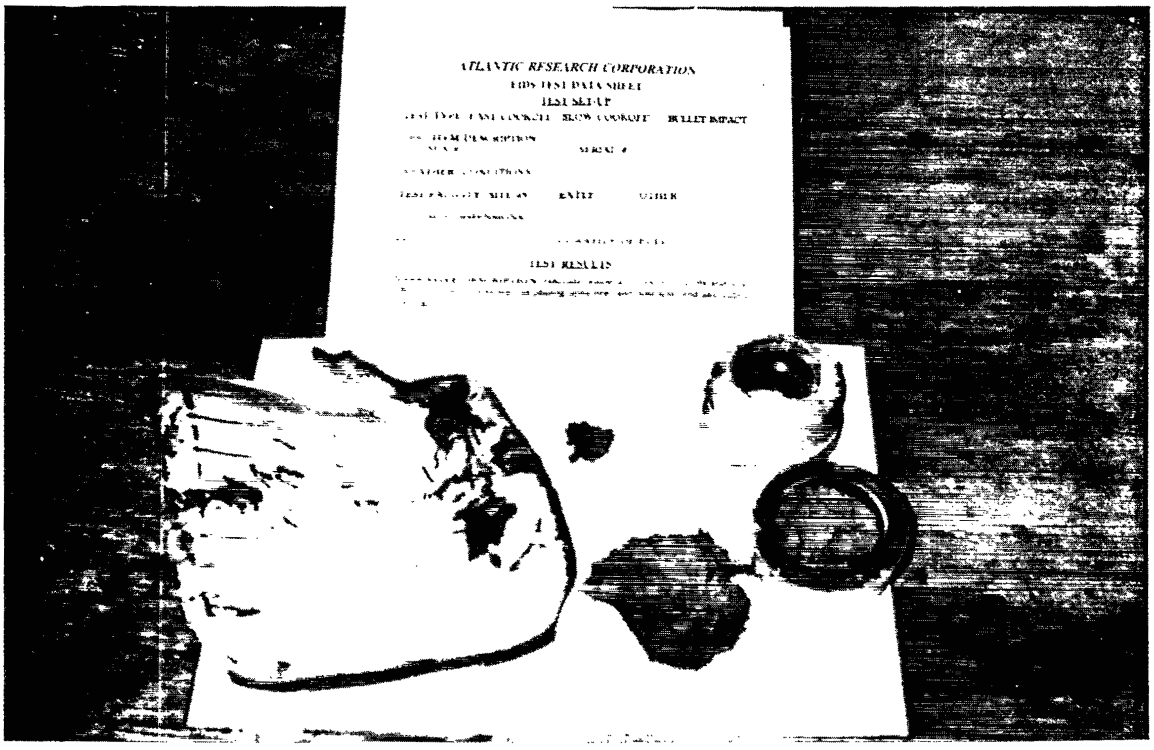

Figure 8. EIDS slow cookoff test results.

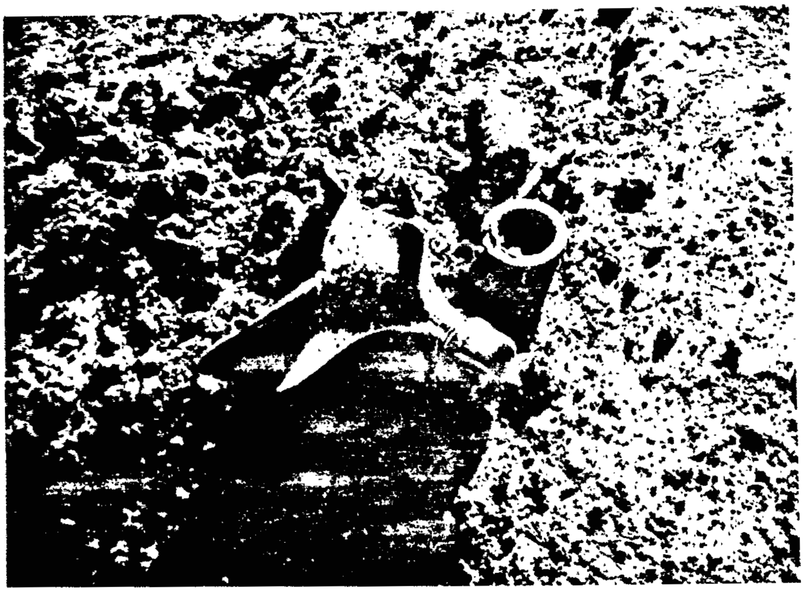

Figure 9. Effect of using welded seamed pipe instead of seamless.